Progress on the NDE Characterization of Impact Damage in Armor Materials

Joseph M. Wells, Sc.D.

XCT

JMW ASSOCIATES

102 Pine Hills Blvd
Mashpee, MA 02649-2869
(508) 477-5764
jmwconsultant@comcast.net

Terminal Ballistics Oral Session #1 - Abstract #1854

22nd International Symposium On Ballistics; Nov.15, 2005 — Vancouver BC, Canada

Grateful Acknowledgements to:

W.H. Green, and N.L.Rupert, ARL Weapons & Materials Research Directorate, APG, MD, 21005

2002 ARL Summer Students

Mr. Jeff Wheeler (UCSC),

Mr. Herb Miller, (UMBC)

Dr. S.J. Cimpoeru, DSTO Aeronautical and Maritime Research Laboratory, PO Box 4331, Melbourne 30001, Australia

Dr. Christof Reinhart, Volume Graphics Gmbh, Heidelberg, Germany

Talk Outline

- Introduction – Challenge for Ceramic Armor
- Perspective on Damage Diagnostics & Cognitive Visualization
- Advanced 3D Voxel Analysis & Visualization
- 3D XCT Damage Characterization & Visualization
- Summary Comments

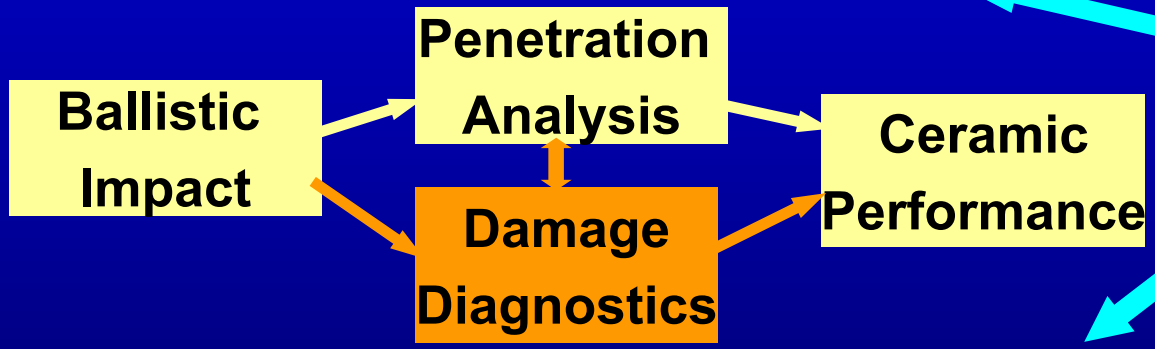
Challenge for Ceramic Armor

Ancient Chinese terra cotta armor vest

- History: Application of ceramic armor against high L/D penetrators is in its' third millennium.
- Still Searching for Best Ceramic Armor !
- Knowledge & Understanding - to design, make and apply notional ceramic armor materials.

Perspective – Damage Diagnostics & Performance

- **Penetration Analysis:**
  - DOP, V50, Field Ballistic Tests



DESIGN BASIS:

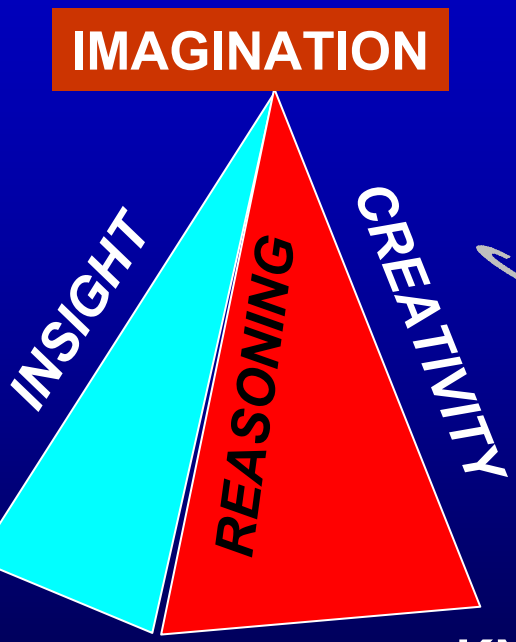
- Theoretical
- Empirical & Numerical Computational Focus
- Diagnostic/ Analytical & Mechanistic Focus

- **Damage Diagnostics & Assessment:**
  - Destructive Sectioning & 2D Examination
  - Traditional Nondestructive Examination
  - High Resolution X-ray Computed Tomography, XCT, for 3D Diagnosis
- Ideally we want a Engineering Predictive Modeling Capability addressing both penetration & damage considerations.

Perspective on Problem Solving & Cognitive Visualization

"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world." – Albert Einstein

Define Problem (Challenge)
- Create Engineering Approach (Plan)
- Data (Acquire & Process)
- Information (Analyze)
- Knowledge (Understanding)
- Visualization (Intellectual Conceptualization)
- Creativity (New Ideas)
- Innovation (Putting Ideas to Work)
- Applications (Utilization of Technology)
- Presentation & Reporting



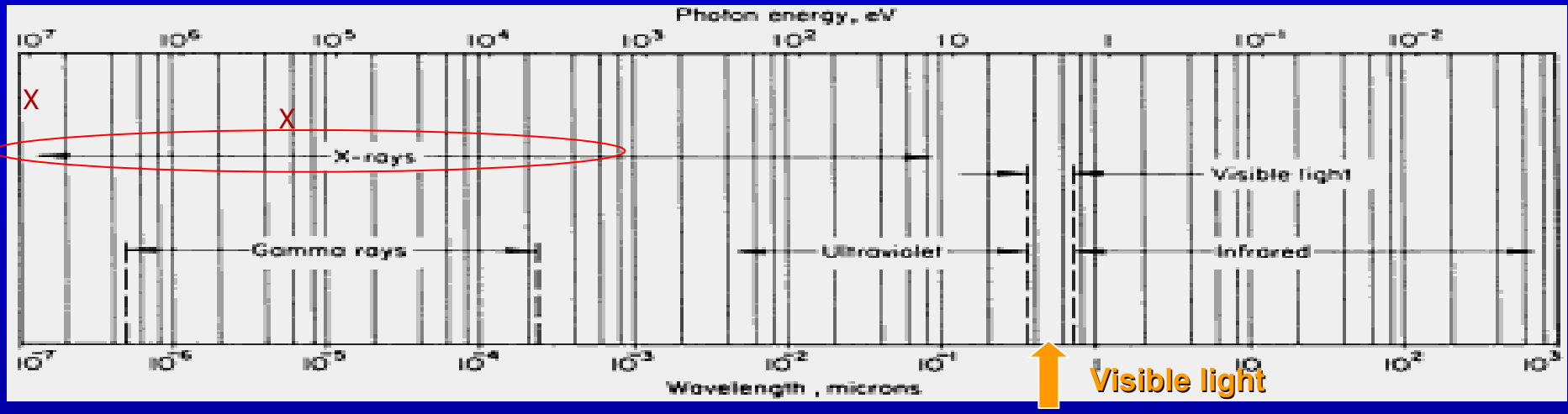
Cognitive VISUALIZATION

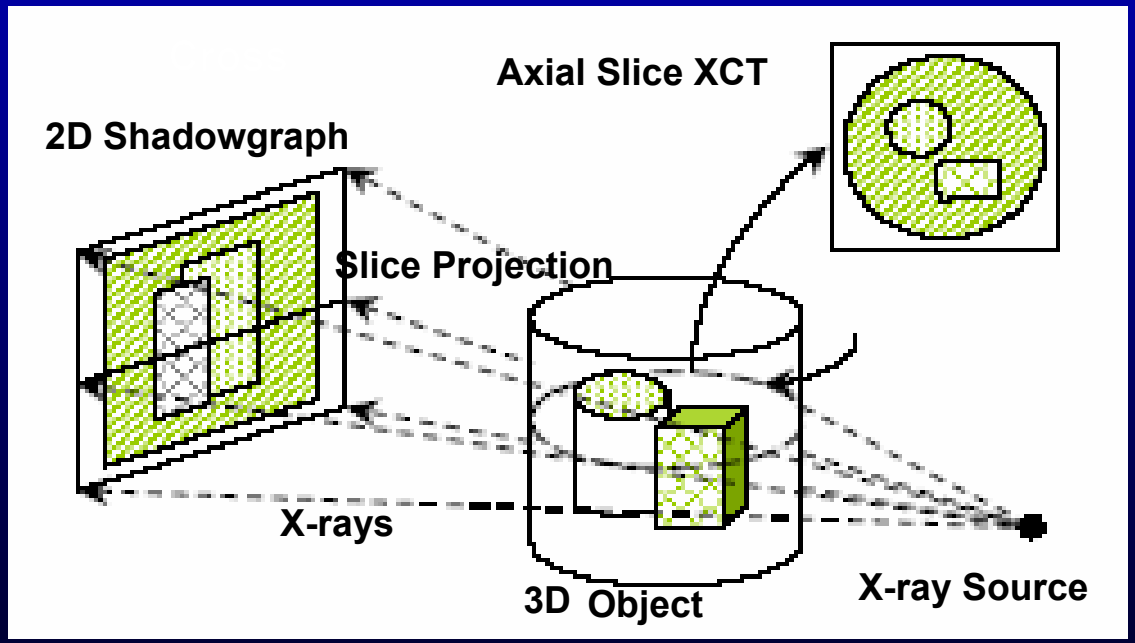
XCT Digital Image Scans

Image Processing & Reconstruction

Understanding of feature relationships & significance

Primer on Modern XCT





Advanced 3D Voxel Visualization & Analysis Software

StudioMax v1.2.1

www.volumegraphics.com

- Sophisticated image analysis and visualization capability to process, analyze and visualize voxel/volume data.
- Up to 3 GB of memory utilization with Windows XP Professional OS
- Multiple Import/Export File Formats
- Virtual Metrology Capabilities
- Variable Transparency & Virtual Sectioning
- Iso-Surface Extraction
- Segmentation & Grey-Value-Classification
- Porosity / Defect Analysis
- Wall Thickness Analysis
- Stereo Viewing Tool

Ballistic Impact Damage Diagnostics in Encapsulated TiB_2 Ceramic Targets

Encapsulated TiB_2 Experiment (N.L. Rupert, ARL ~1997)

- **Single Shot (Full Penetration w/o compressive ring)**
- **Single Shot (Partial Penetration with compressive prestress ring)**
- **Double Shot (Full Penetration with compressive prestress ring)**

Summary Damage Observations

Penetration Decrease with Prestress (17-4 PH Ring)

Surface Topography – Ring Steps, Radial Expansion & Cracking

W-alloy Residual Fragments

Complex Cracking Modes

Impact Induced Porosity

Impacted TiB2 Ceramics

Macro –Photos

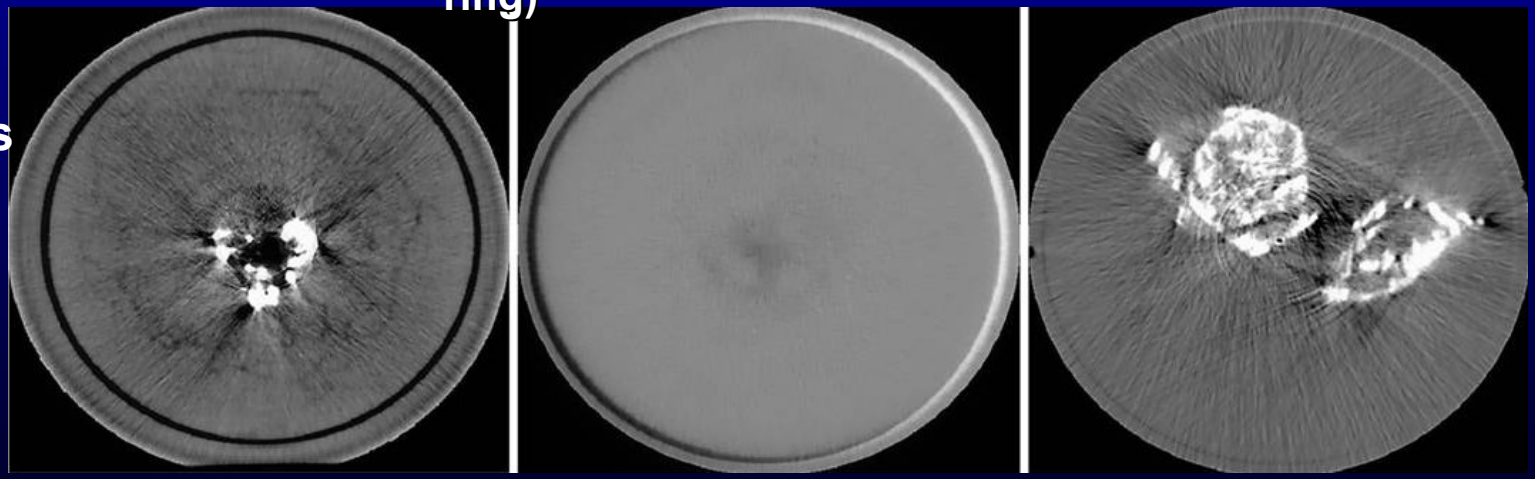
Impact surface

Single Shot (Full Penetration w/o compressive ring)

Single Shot (Partial Penetration with compressive prestress ring)

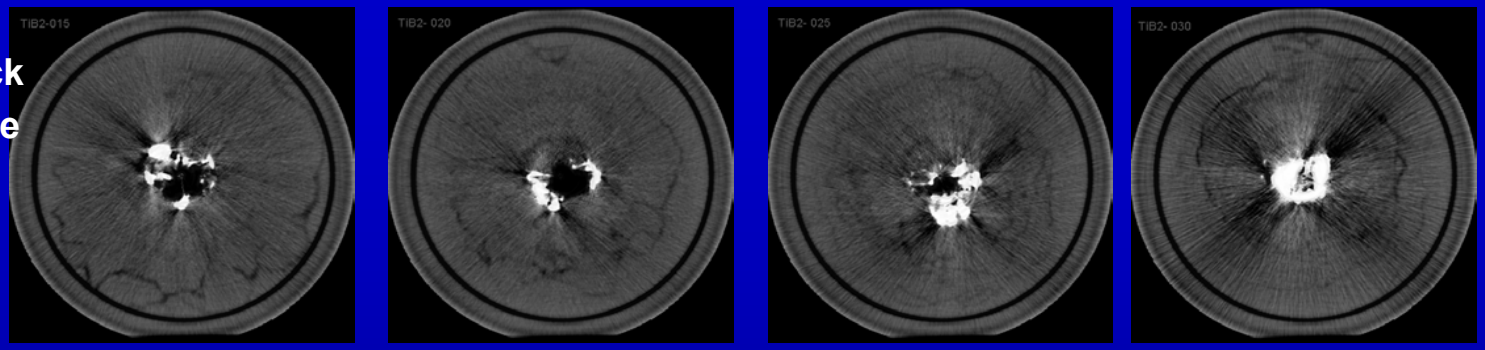
Double Shot (Full Penetration with compressive prestress ring)

XCT Scans ~ mid-thickness

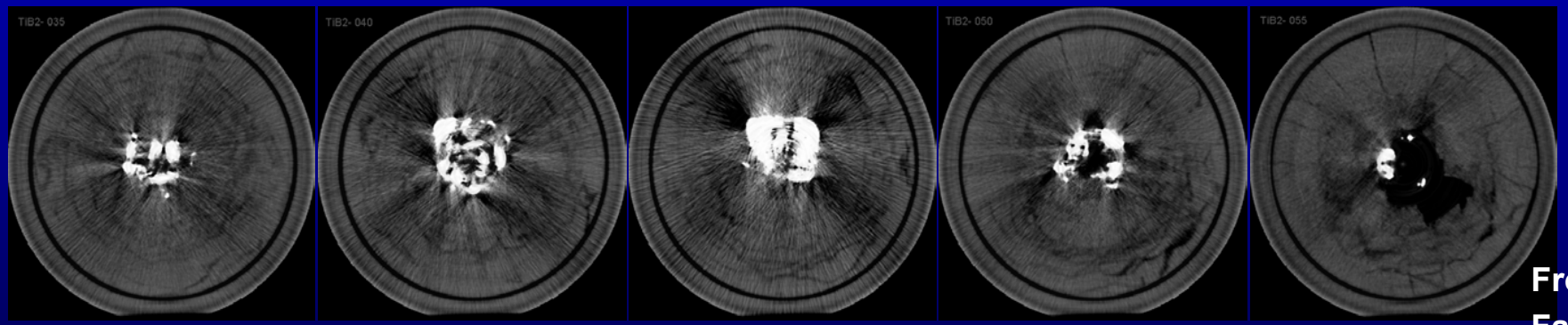


Penetration & Internal Damage

Back Face



(z = 015) (z = 020) (z = 025) (z = 030)



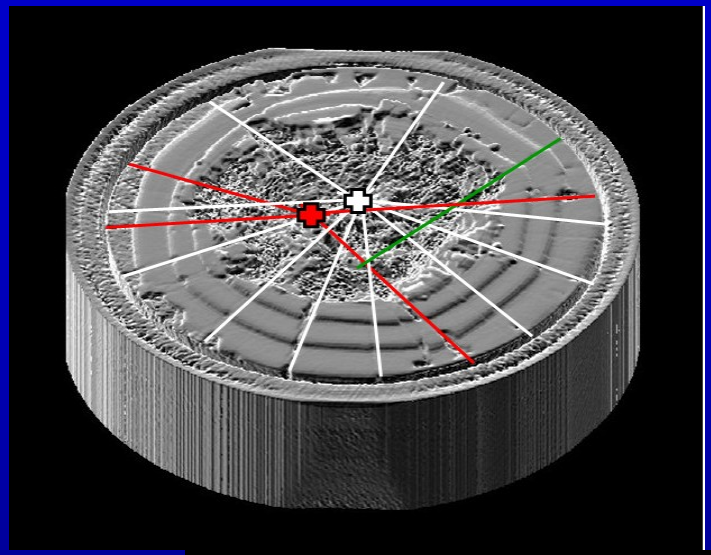
Front Face

(z = 035) (z = 040) (z = 045) (z = 050) (z = 055)

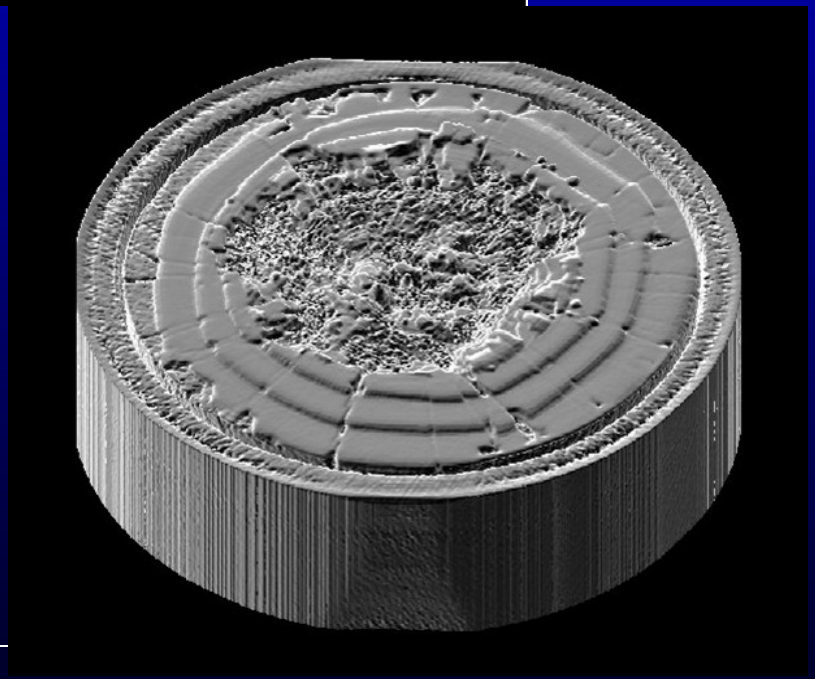
Sequential XCT Scans showing impact damage cracking features and residual penetrator (white) in TiB_2 S1wo Disk - near back (Z=015) to front face (Z=55).

Surface Topography -TiB_2 1S w/o prestress

Macro-photograph - Normal View
*Surface Steps – **NOT** Visable*
Radial OD Cracks – ARE Visable

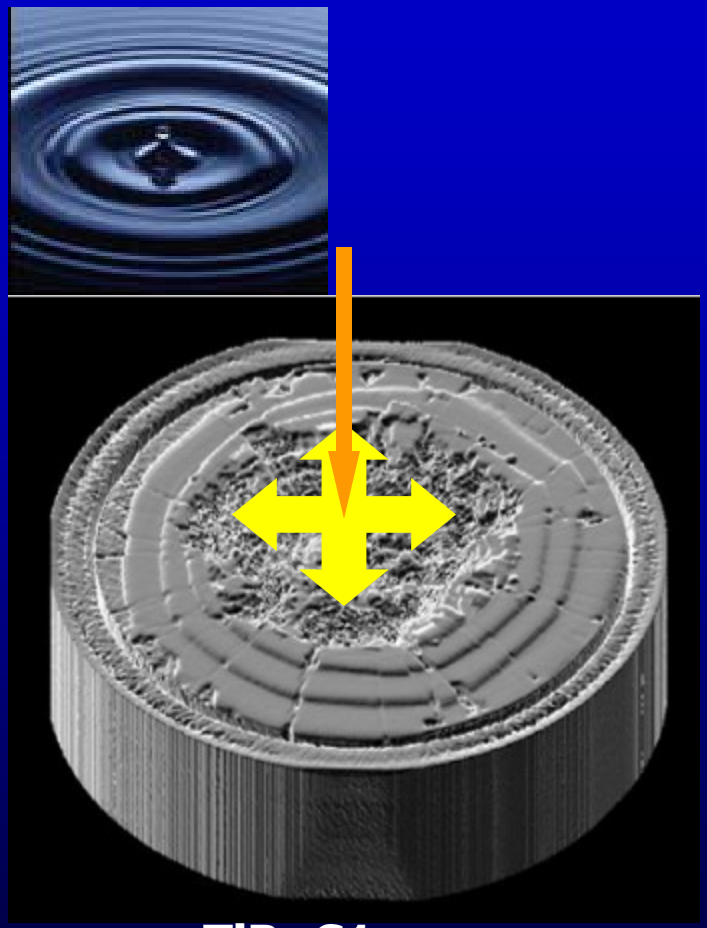


OD Radial cracks on Impact Surface **intersect at different loci**



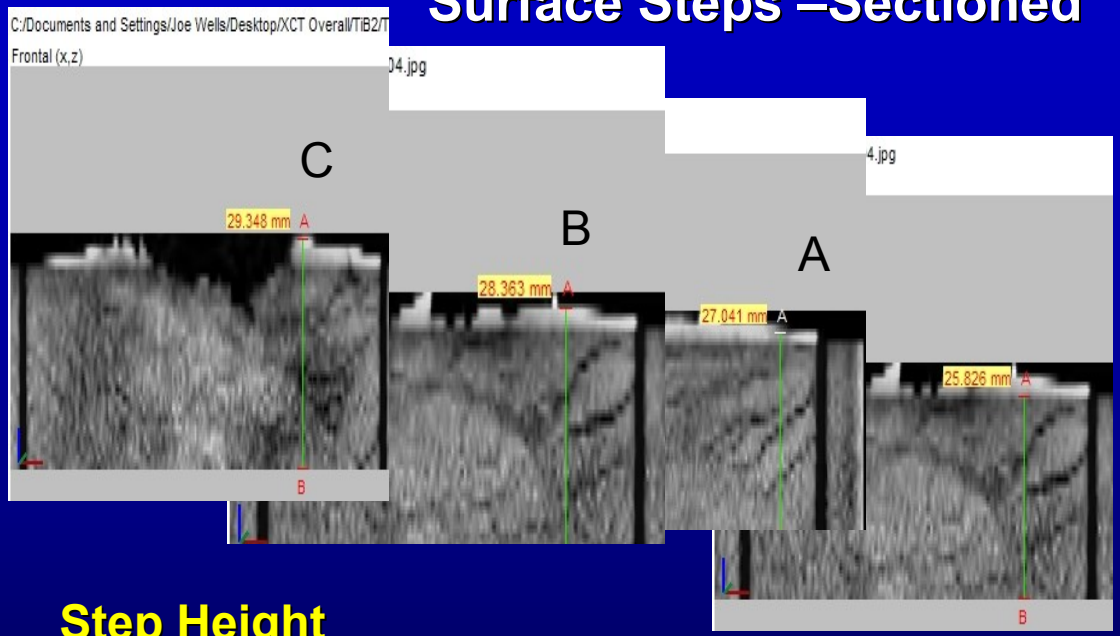
XCT 3D Solid Object - Oblique View
Surface Steps – ARE Visable
Radial OD Cracks – ARE Visable

Impact Surface- Flow of Mixed Penetrator & Ceramic Rubble



TiB_2 S1wo

Surface Steps –Sectioned



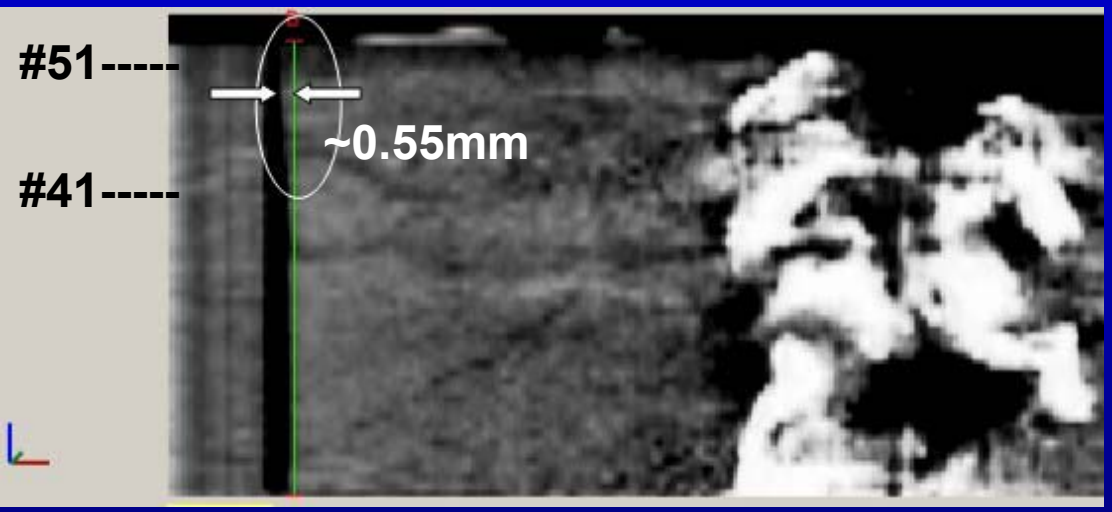
Step Height
C = ~3.5 mm
B = ~2.5 mm
A = ~1.2 mm

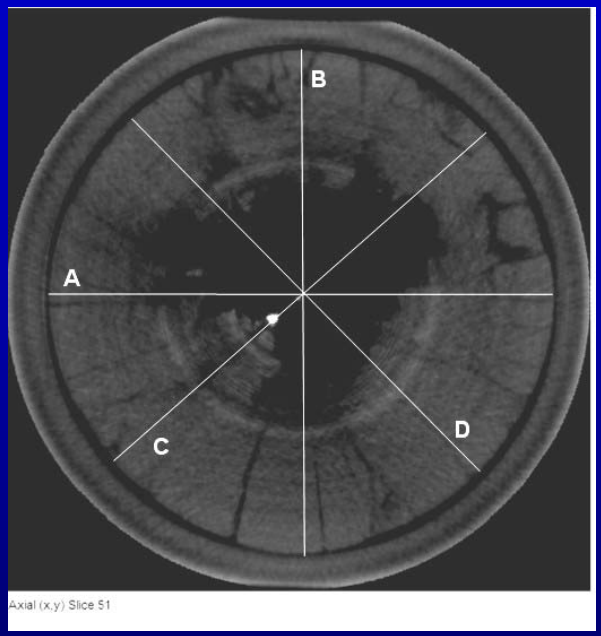
Step Heights Vary along the ring circumference

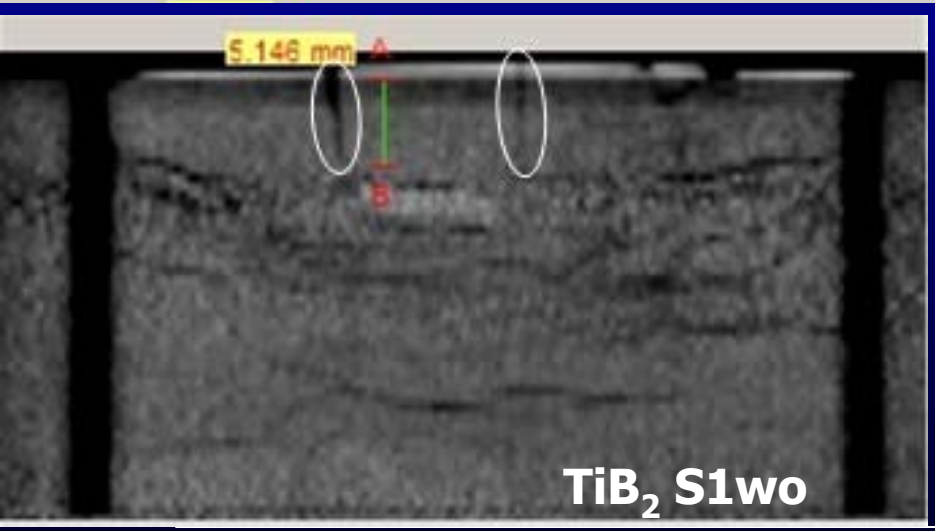
Note: Higher density (lighter color) of Steps vs Bulk TiB_2

Impact Surface Radial Expansion

Nonuniform – but localized radial expansion near impact surface

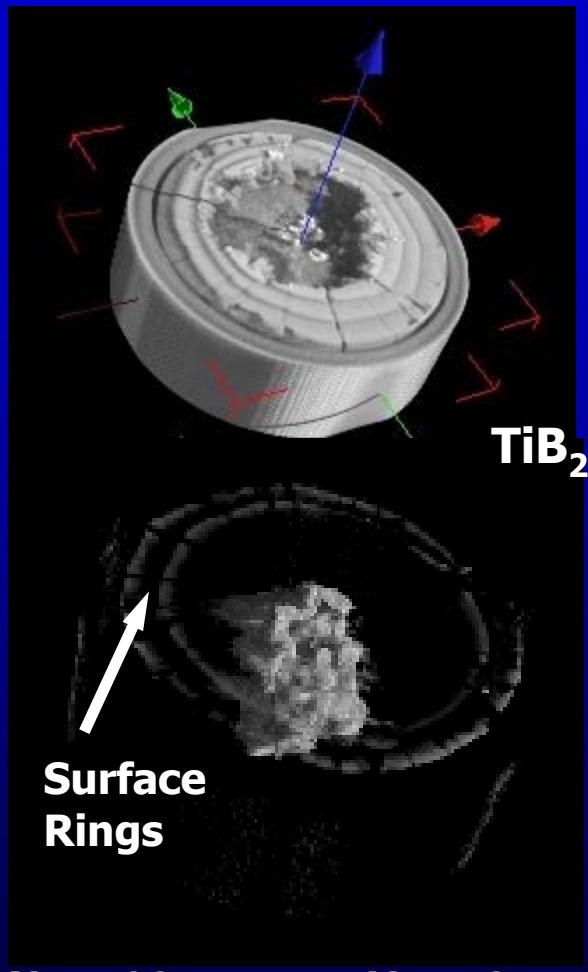






Axial Slice #51		Axial Slice #41
Dia. A = 73.8 mm	→	Dia. A = 72.7 mm
Dia. B = 73.4 mm		Dia. B = 72.9 mm
Dia. C = 72.3 mm		Dia. C = 72.1 mm
Dia. D = 72.4 mm		Dia. D = 72.0 mm

Fragments in TiB_2 - Segmented & Virtual Transparency



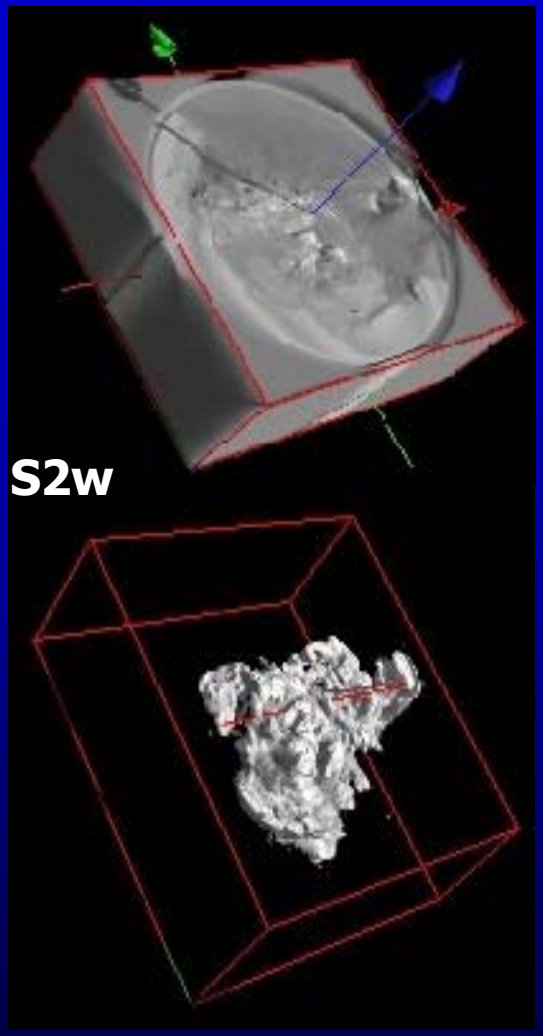
TiB_2 S1wo

Surface Rings

Opaque 3D Solid Object Reconstructions

Segmented & Variable Transparency

Fragments are Porous



TiB_2 S2w

Virtual Metrology

W = ~22 mm H = ~24.5 mm

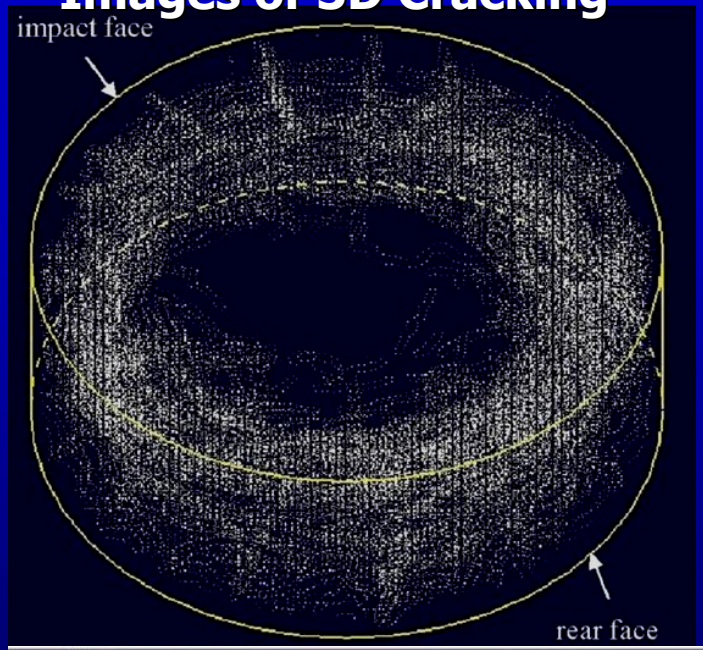
A_s = 4794 mm^2 V = 2076 mm^3

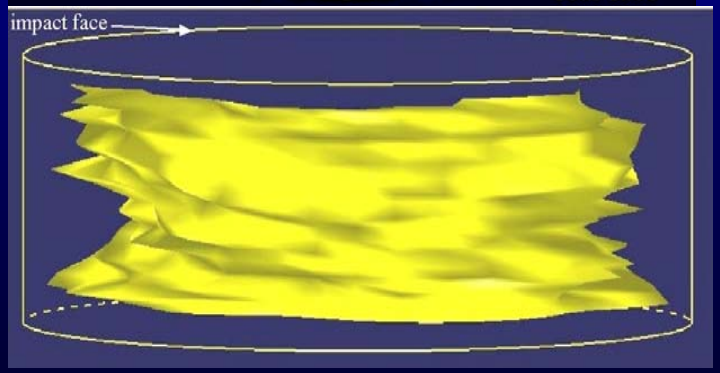
W = ~60 mm H = ~25.5 mm

A_s = 8911 mm^2 V = 2859 mm^3

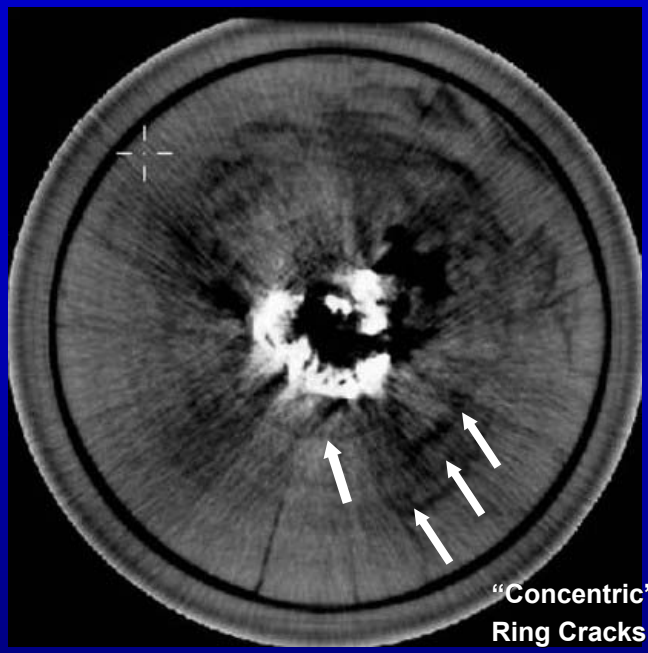
Complexity of 3D Ring Cracking Damage

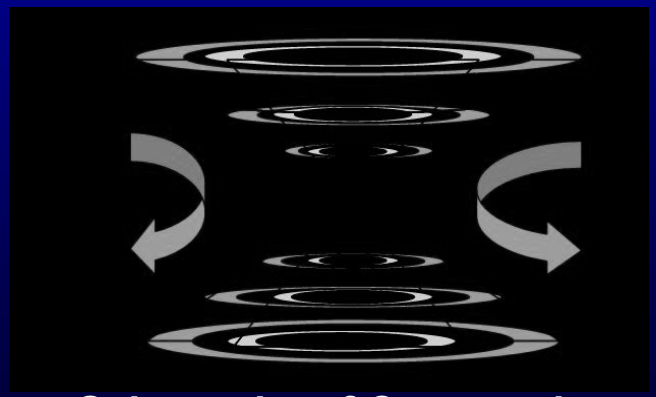
Early Point Cloud Images of 3D Cracking





TiB2 1S w/o Prestress Ring

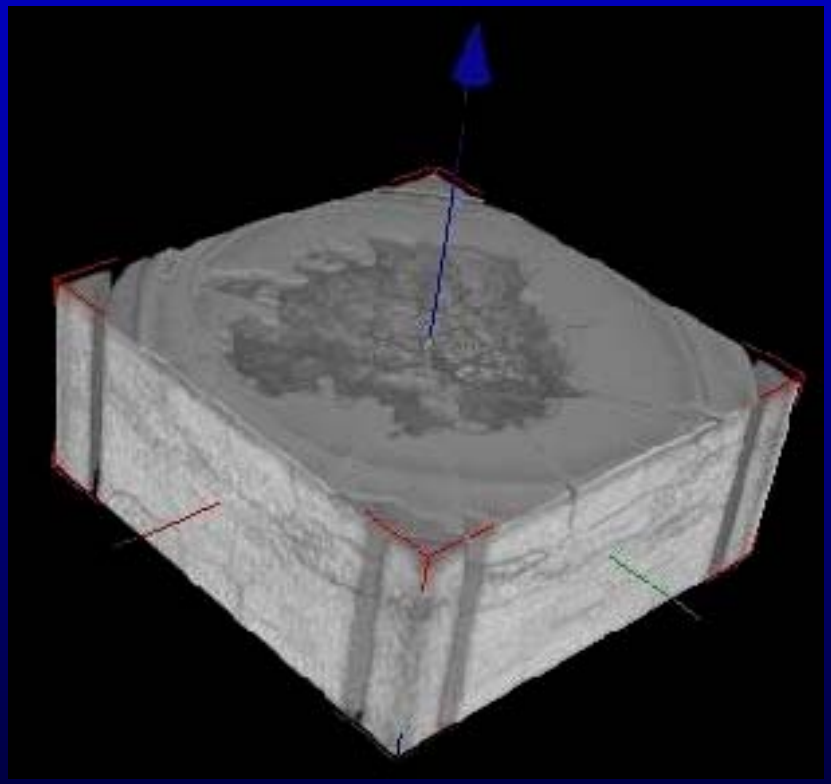




Schematic of Concentric Hourglass Ring Cracking

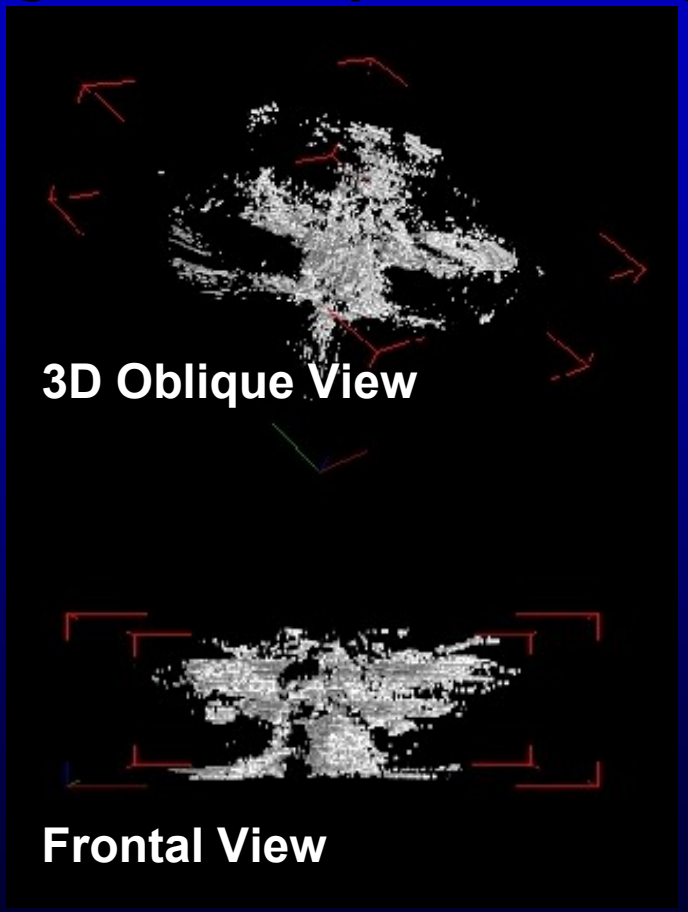
Visualization of 3D Cracking Damage in TiB_2

Orthogonal Sectioning
3D Oblique View

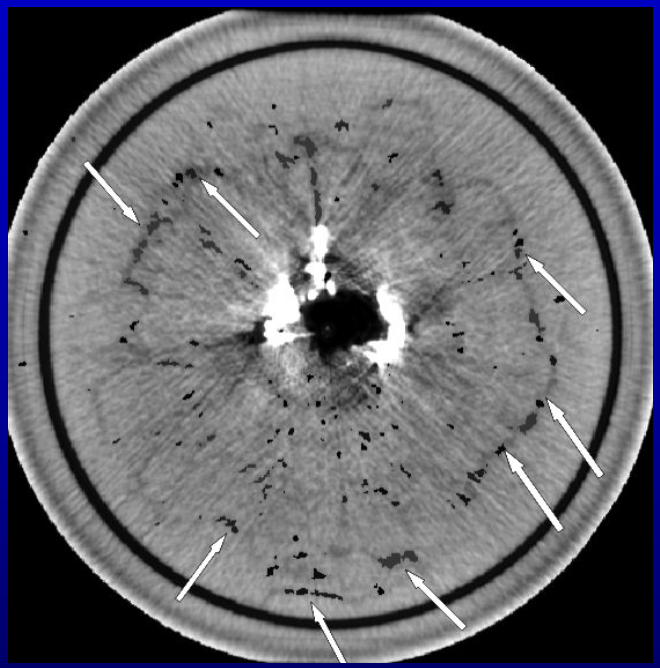


S1wo

Recent (Preliminary) 3D Images of Segmented Impact Cracking

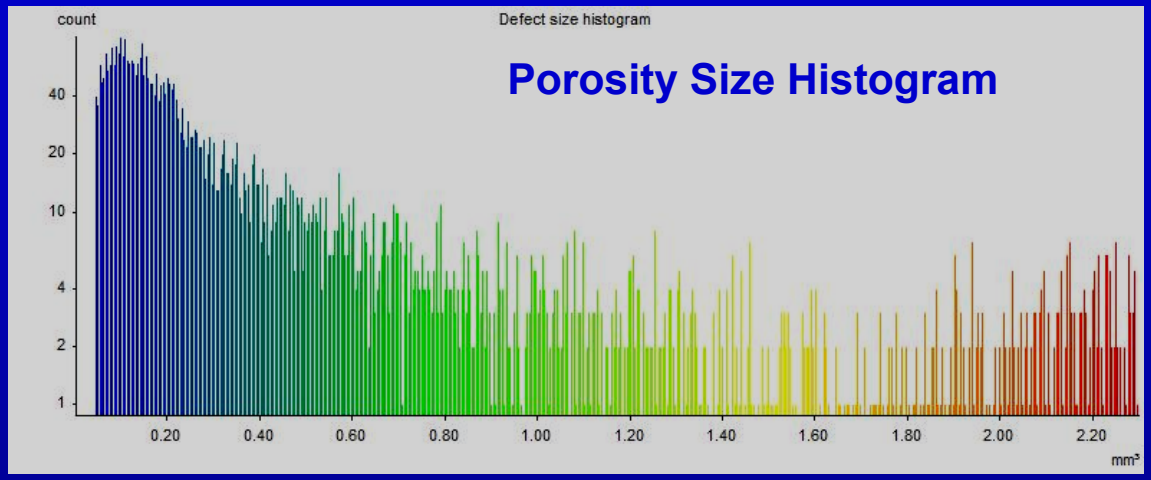


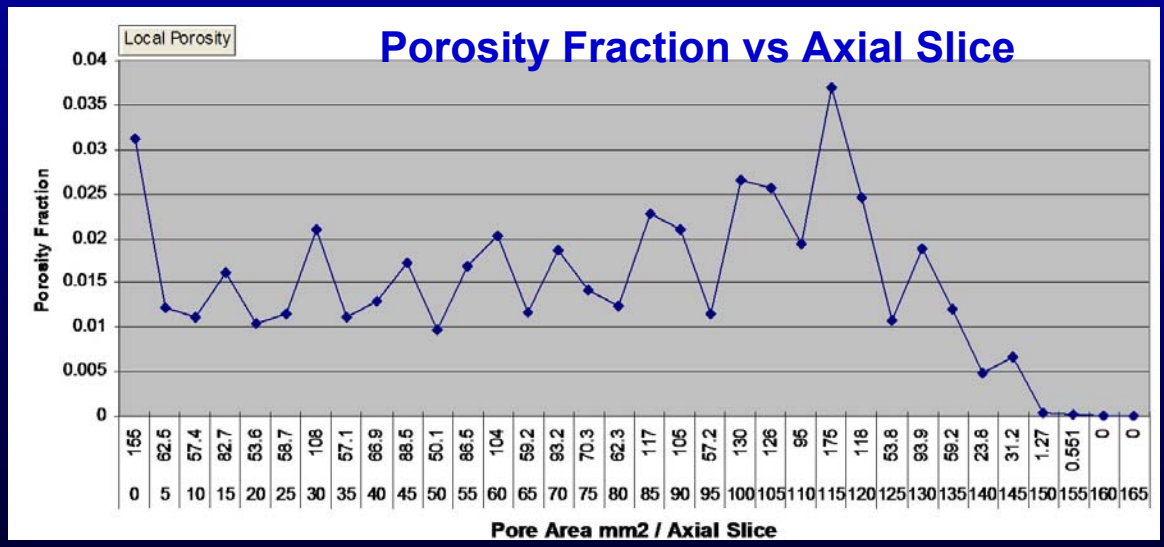
Impact Induced Porosity



Porosity along Ring Cracks

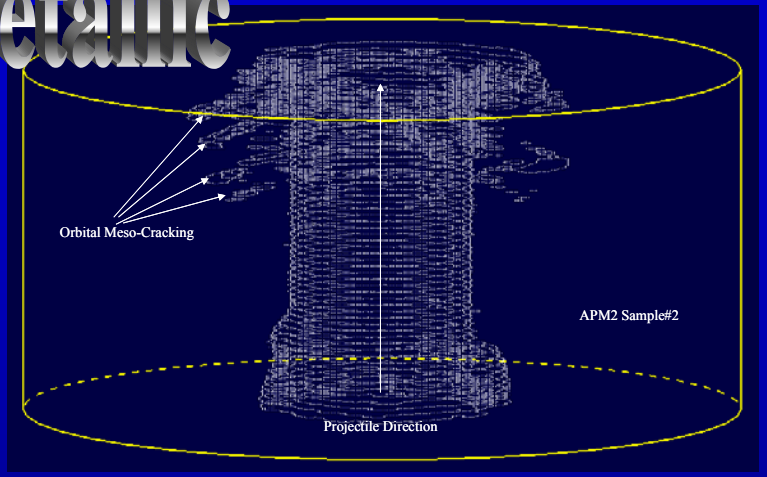
TiB2 1S w/o
Prestress Ring



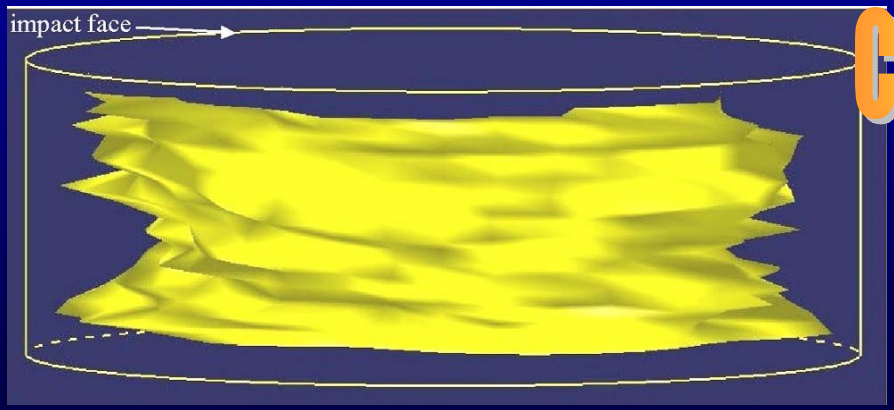


Point Cloud Visualizations of Spiral Cracking in Ballistic Impact Samples

Metallic

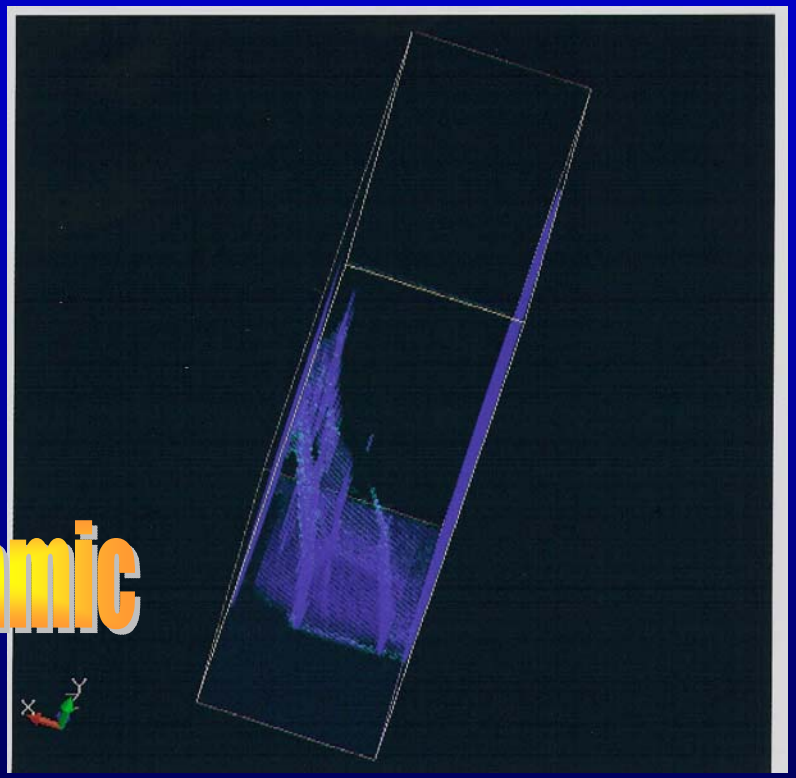


Ti-6Al-4V pc showing spiral cracking
(Full Penetration)



TiB_2 surfaced pc showing spiral
(Dual Impact – Full Penetration)

Ceramic



TiC pc showing spiral- blue
(No Penetration)

Summary Comments

- The NDE Diagnostic Interrogation of Impact Damage in Armor Ceramics is a Challenging Task.
- XCT Diagnostics, Voxel Analysis, and 3D Visualization have revealed new details & insights into:
  - Impact Surface - Topography & Damage
  - Internal Residual Fragment Distribution
  - Internal Mesoscale Cracking Modes
  - Impact-created Porosity/Void Distributions
  - Volumetric (3D) Damage Perspectives
- The XCT Diagnostic approach to armor ceramic Damage Analysis & Visualization is NOT yet widely practiced.
- Further Improvements in and Benefits from this technique are possible and realistically anticipated.

As far as the laws of mathematics refer to reality, they are not certain: and as far as they are certain, they do not refer to reality" – A. Einstein